JOURNAL OF BALTIC SCIENCE EDUCATION

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

DIFFERENCES IN TEACHING AND LEARNING CONCEPT NETWORKS OF PHOTOSYNTHESIS ACCORDING TO ACHIEVEMENT LEVELS

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Abstract. *Students comprehend most science concepts through in-class learning. Therefore, how teachers present concepts can decisively influence students' understanding of scientific concepts. Accordingly, this study aimed to identify implications for concept teaching and learning by comparing the conceptual structure of photosynthesis reflected in the teaching concept networks used by teachers with the learning concept networks constructed by students. In this process, the construct of the concept network taught by the teacher and the concepts learned by students at each achievement level were compared and analysed using semantic network analysis. The concepts taught by the teacher and those learned by the students were largely similar, but the strength and complexity of the connections between concepts differed. Moreover, the teacher did not clearly distinguish between subtopics while teaching. As a result, the students recognised the concepts but often failed to distinguish between subtopics. High-achievers learned more concepts and showed a more complex connection between concepts than low-achievers. The findings suggest that teachers should explain scientific concepts by breaking them down into subtopics and presenting them in smaller, interconnected chunks to help students relate new knowledge to existing knowledge.*

Keywords: *achievement level, concept network, connected concept network, learning concept, teaching concept*

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Introduction

Beyond academia, science and technology are integral to daily life in modern society. Science education is highly valuable because it helps people develop the thinking skills needed to understand complex problems and make informed decisions. Helping students understand scientific concepts is one of the most critical goals of science education (Ministry of Education, 2015; Smith & Siegel, 2004). Because knowledge in scientific subjects can be challenging to acquire independently, students learn most science concepts in class (Mallow, 1986; Pianta & Hamre, 2009; Schenke et al., 2017).

The learning content presented by teachers is reconstructed by students, organising and retaining concepts within their own cognitive frameworks. While experts have a rich schema related to the learning content, novices do not (Feldon, 2007), leading to differences in how they structure knowledge. This dynamic applies equally to teachers and students, as well as to experienced and novice teachers. However, many teachers tend to focus on simply conveying conceptual knowledge without considering how students understand and structure the concepts (Widodo & Duit, 2002; Widodo et al., 2002). How knowledge is structured affects how it is understood and applied (de Jong & Ferguson-Hessler, 1996). Therefore, this study analyses the conceptual structures that teachers use to teach students and the conceptual structures that students use to acquire and structure what they are taught.

Semantic network analysis (SNA) is a widely used method for analysing conceptual networks within cognitive structures (Koponen & Nousiainen, 2014; Yun & Park, 2018). SNA can be used to infer the connection among concepts within a learner's cognitive structure using linguistic or textual data (Drieger, 2013). This method facilitates the specification of abstract semantic structures by analysing the connections between concepts and visualising hidden networks (Doerfel & Barnett, 1999).

Studies have examined the connections between concepts presented in textbooks using the SNA method (Yun & Park, 2018), as well as how these connections appear across curricula, textbooks, lessons, and assessments (Park et al., 2018). Additionally, researchers have compared the concept networks used by teachers during instruction with the concept networks that students actually form after learning (Kim et al., 2023; Lim et al., 2025). However, research has yet to examine the effect of specific learner variables in

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

actual school science classes. Accordingly, this study compares learner variables by considering academic achievement, a critical outcome of science education.

Many studies have been conducted on the connection between academic achievement and learner variables in science education, with most analysing the factors affecting this achievement (Fraser, 1994; Greenfield, 1996; Ma & Wilkins, 2002; Reynolds & Walberg, 1992; Singh et al., 2010; Wang & Staver, 1996). Previous studies have used academic achievement as the dependent variable and only analysed the manipulated variables influencing it, failing to directly examine the changes occurring due to differences in achievement. Therefore, this study comparatively analyses students' conceptual structures after learning according to their academic achievement level, with photosynthesis selected as the conceptual topic.

Understanding photosynthesis is critical to understanding the key scientific concept of metabolism, an important science curriculum topic (Marmaroti & Galanopoulou, 2006). Students often struggle to understand the concept of photosynthesis because it requires forming connections between difficult and complex concepts (Marrnaroti & Galanpoulou, 2006; Stavy et al., 1987). Accordingly, it is necessary to investigate differences in students' acquired concepts and their conceptual connections across achievement levels through semantic network analysis.

The Republic of Korea follows a national curriculum for 1-12 education. It presents achievement standards that combine specific learning content with the expected abilities students should demonstrate after instruction. These standards serve as practical guidelines for teaching and assessment. Photosynthesis is taught progressively across elementary, lower-, and upper-secondary school. In elementary school, instruction focuses on how plants obtain nutrients and the role of light. In lower-secondary school, students learn about the site of photosynthesis, the necessary reactants, its products, and the environmental factors that influence it. In upper-secondary school, photosynthesis is covered in depth from the perspective of energy conversion and metabolism. This study focused on lower-secondary school students because this is the stage at which concepts related to photosynthesis become increasingly important.

Theoretical Background

Photosynthesis Content Presented in the Republic of Korea's Curriculum and the Next Generation Science Standards

In the Republic of Korea, photosynthesis content in the lower-secondary school science curriculum is taught in the eighth grade as part of the 'Plants and Energy' unit. Students learn about photosynthesis by understanding how plants obtain energy, including how they make nutrients and use them to obtain the energy needed for life activities (Ministry of Education, 2015), reflecting students' expected achievement standards. Additionally, the curriculum presents related inquiry activities that explore the site of photosynthesis, its products, and environmental factors affecting it (Ministry of Education, 2015).

The Next Generation Science Standards for lower-secondary schools in the United States position photosynthesis as a fundamental process involving the flow of matter and energy in organisms, as well as its significance in chemical reactions and daily life (NGSS Lead States, 2013). That is, it focuses on tracking the movement of materials and the flow of energy but overlooks the biochemical mechanisms of photosynthesis.

Conceptual Connection Errors

Science learning is a process of concept construction (Riemeier & Gropengieber, 2008). Through classroom interactions, students actively and independently construct meaning (Amineh & Asl, 2015). However, during this process of concept construction, students make incorrect inferences and conceptual connection errors (Confrey & Lipton, 1985).

Conceptual connection errors in learning may produce learning deficits (Lim, 2019). In a study on classroom instruction about cell division, Lim (2019) found that the absence of some concepts and errors in the connections between concepts contributed to learning deficits.

Experts' problem-solving strategies have a lower error frequency and are more effective than beginners' problem-solving strategies (Jitendra & Kameenui, 1996). Recent studies have sought to identify the causes of learning deficits by comparing structural differences between teaching concept networks and learning concept networks, particularly errors in the connections between concepts perceived by students or the absence of key concepts (Kim et al., 2023; Lim et al., 2025). Meanwhile, although many studies have explored factors that may

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

affect achievement in science education, few have examined the specific conceptual reasons for differences in achievement. Therefore, this study analysed achievement differences at the conceptual level by comparing teaching and learning concept works according to students' achievement levels. The research questions were as follows:

- How do teachers' teaching concept networks and students' learning concept networks of photosynthesis differ?
- How do students' learning concept networks of photosynthesis differ according to academic achievement levels?

By exploring these questions, this study seeks to identify potential conceptual factors associated with academic deficits at the conceptual level perceived by students, with implications for teaching and learning.

Research Methodology

Design

This study used network analysis to compare teachers' teaching concepts and students' learning concepts regarding photosynthesis in lower-secondary schools in the Republic of Korea. Network analysis complements the limitations of qualitative research methods in analysing teaching and learning processes (Lee & Choi, 2019). The independent variable was teachers' teaching concept networks, and the dependent variables were students' learning concept networks across achievement levels on photosynthesis. Because the three teachers followed similar instructional approaches, their lessons were aggregated to construct a single teaching concept network for comparison with students' learning concept networks.

The teaching concept networks were constructed by analysing recordings of the teachers' lessons on photosynthesis. The student learning concept networks were constructed from the concepts they expressed in the open-ended photosynthesis learning concept questionnaire and visualised as semantic networks. The classes were conducted from May to June 2023, according to the curriculum progress plan of participating schools. And the analysis of the research results took approximately six months.

Participants

The participants were students and teachers from three lower-secondary schools in a metropolitan city in the Republic of Korea with a population of 2.5 million people. The researchers explained the purpose and method of the study in advance. Participants comprised a science teacher from each of the three schools and the 129 13- to 14-year-old eighth-grade students they taught. The teachers were all eighth-grade science teachers, one male and two females. One had four years' work experience, while the other two had over fifteen. Two had a master's degree, while the other had a bachelor's degree. All teachers and students agreed to participate. Students and teachers were informed of the guarantee of anonymity, and their written consent was obtained. In the case of students, prior consent was obtained from their parents on their behalf. The participating students had high science achievement levels, ranking in the top 30% nationally. Accordingly, this relatively homogenous group offered the advantage of yielding a stable semantic structure.

This study excluded 31 students who did not respond to the questionnaires or provided irrelevant answers. Therefore, the study analysed data from the 98 students (male: 59, female: 43) who responded to the test immediately after class. Although data from only 98 students were analysed, the resulting semantic networks showed a relatively high average density of .180 (.119– .273). This high density suggests strong agreement among students and a robust, well-structured shared understanding of photosynthesis (Doerfel & Barnett, 1999; Scott, 2017).

Classes Related to Photosynthesis

Photosynthesis content was taught in three classes between May and June 2023, according to the curriculum progress plan of participating schools. It consisted of lessons on 'photosynthesis reactants', 'photosynthesis products', and 'environmental factors'. Each subtopic was taught in a 45-minute lesson that combined direct lecture-style instruction with inquiry-based experiments.

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

The lesson on 'photosynthesis reactants' identifies water and carbon dioxide as the substances that plants need for photosynthesis. First, the teacher compared how animals and plants obtain the energy needed to live and explained that plants need photosynthesis to obtain energy. The teacher and students conducted an experiment using bromothymol blue to identify the substances necessary for photosynthesis by observing colour changes.

The lesson on 'photosynthesis products' conveyed that plants produce glucose, a nutrient, and oxygen, a by-product, through photosynthesis. The teacher demonstrated an experiment using *Hydrilla verticillata* to teach students about starch production during photosynthesis. The teacher explained that photosynthesis occurs in the chloroplasts of leaves, where glucose is converted into starch for temporary storage. Students collected the gas produced from photosynthesis and confirmed through a separate experiment that it was oxygen, a by-product of photosynthesis.

The lesson on 'environmental factors' explained the environmental factors affecting photosynthesis. The Republic of Korea curriculum stipulates that students should learn how light intensity, carbon dioxide concentration, and temperature affect the rate of photosynthesis. The teacher conducted an experiment to measure the time it takes for pieces of spinach leaves (of equal size) to float in water, depending on the number of light sources. This experiment demonstrated changes in the rate of photosynthesis according to light intensity. In addition, the influence of temperature and carbon dioxide concentration was investigated by interpreting graphs of changes in the photosynthetic rate.

Questionnaire

The questionnaires consisted of a photosynthesis achievement questionnaire and a photosynthesis learning concept questionnaire, divided into the three subtopics of 'photosynthesis reactants', 'photosynthesis products', and 'environmental factors'.

The photosynthesis achievement questionnaire was a multiple-choice test based on the class goals and content of the photosynthesis unit in eighth-grade science. It consists of five questions per topic. Two current teachers with master's degrees and three with doctoral degrees tested the validity of the questionnaires, and the content validity index of each item ranged from .712 to .888. Items that received low scores were revised based on feedback from a specialist in life science education. Additionally, the reliability (Cronbach's α) of the questionnaire was .738, indicating statistically appropriate validity and reliability.

The photosynthesis learning concept questionnaire was modified and adapted from the tool used by Lim et al. (2025) to suit the photosynthesis topic and subtopics. The questionnaire provides simple examples of the unit, learning objectives, related pictures, and tips for filling it out. The questionnaire was developed with open-ended questions so students could freely describe what they had learned immediately after class. An example of the questionnaire for 'photosynthesis reactants' is presented in Appendix 1. Only the learning objectives and related pictures differed for each subtopic.

Data Collection and Analysis

To examine the teaching and learning concepts, recordings of the teachers' instruction and the students' responses to the questionnaires on photosynthesis learning were collected and analysed. The photosynthesis learning concept questionnaires were administered immediately after each subtopic lesson, and the photosynthesis achievement questionnaires were administered the morning after the class. These questionnaires were completed online using tablets provided by the school and administered under the science teacher's supervision. Students were given approximately 10 to 15 minutes to complete the questionnaire.

The collected data were analysed as follows. First, the photosynthesis achievement questionnaire scores were used to divide students' achievement levels into high, middle, or low. A correct answer to the photosynthesis achievement questionnaire was given one point, and an incorrect answer was given no points. Based on the scores obtained, students were categorised into high-, middle-, or low-achievers according to the ranking percentile. Those with a ranking of more than 27% were classified as 'high-achievers', the group with the lowest 27% were 'low-achievers', and the rest were 'middle-achievers'.

Network analysis consisted of three main stages: pre-processing, network structuring, and metric calculation based on the network. First, the responses to the photosynthesis concept questionnaire were transcribed sentence by sentence and saved as a .txt file, organised by subtopic. To extract only scientific concepts from the transcribed files (.txt), pre-processing was performed using the NetMiner 4.0 program (Lee, 2014). Non-scientific concepts

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

such as prepositions, adverbs, and adjectives were excluded or unified into one synonym (e.g., 'H_20' is categorised as 'water'). This process yielded 73 concepts. Current science teachers were asked to identify meaningful scientific concepts in life sciences among the 73 selected concepts. These teachers comprised five lower-secondary school science teachers, four with master's degrees and one with a doctoral degree. Only concepts identified as meaningful by three or more teachers were included in the analysis, resulting in a final 47 concepts.

Using these concepts, the second step—concept network visualisation—was performed using the NetMiner 4.0 program. In a 1-mode network, items with identical attributes are compared, while in a 2-mode network, items with different attributes are compared. Therefore, the teachers' and students' concept networks for each subtopic were analysed using a 1-mode network, and the connection network for comparing the teaching and learning concepts was analysed using a 2-mode network.

Finally, network metrics were calculated. To analyse differences in learning concept networks according to achievement levels, frequency, eigenvector centrality, number of links, and average degree were analysed. Frequency and eigenvectors were used to identify the key concepts in the learning concept networks according to students' achievement levels, while the number of links and average degree were used to compare learning concept networks based on achievement levels.

Research Results

Concept Network

Photosynthesis Reactants

The teaching concepts network for 'photosynthesis reactants' is shown in Figure 1a. A total of 27 concepts is presented, including 'photosynthesis' (112 times), 'carbon dioxide' (96 times), 'light energy' (62 times), 'bromothymol blue' (56 times), and 'water' (51 times). Eigenvector centrality occurs in the following order: 'carbon dioxide' (.613), 'water' (.578), 'photosynthesis' (.346), 'plant' (.288), and 'light energy' (.190). The teaching concepts network centres on scientific concepts such as 'carbon dioxide', 'water', and 'light energy', which are scientific concepts for 'photosynthesis reactants' and are connected to the concept of 'plants'. The teacher taught the subtopic 'photosynthesis reactants' through verification using exploratory activities such as 'bromothymol blue'. However, 'sieve tube' and 'shift' are not connected to other concepts. In class, these concepts are necessary for explaining how the substances produced by photosynthesis are moved and used. Thus, it was confirmed that concepts not directly related to photosynthesis reactants were used in class.

The total number of concepts present in the high-achievers' learning concept network (Figure 1b) for 'photosynthesis reactants' is 27, including 'photosynthesis' (79 times), 'carbon dioxide' (67 times), 'light energy' (62 times), 'water' (51 times), and 'glucose' (38 times). Eigenvector centrality occurs in the following order: 'carbon dioxide' (.631), 'water' (.627), 'light energy' (.395), 'photosynthesis' (.153), and 'plant' (.126). High-achievers recognised the connections between concepts centred on 'light energy', 'plant', 'carbon dioxide', 'water', and 'photosynthesis'. In addition, in inquiry activities, concepts such as 'bromothymol blue' and 'Hydrilla verticillata' were recognised, although the correlation was low.

The total number of concepts shown in the middle-achievers' learning concept network (Figure 1c) is 18, including 'carbon dioxide' (47 times), 'photosynthesis' (46 times), 'water' (24 times), 'light energy' (20 times), and 'glucose' (20 times). Eigenvector centrality occurs in the following order: 'carbon dioxide' (.666), 'water' (.654), 'light energy' (.262), 'photosynthesis' (.187), and 'plant' (.128). Students at the achievement level recognised 'photosynthesis reactants', focusing on the concepts of 'photosynthesis', 'water', 'plant', and 'carbon dioxide'. In addition, lower-achieving students recognised concepts presented in the inquiry activities, such as 'bromothymol blue' and 'Hydrilla verticillata', although the correlation was low. However, the connection between 'glucose', 'nutrition', and 'oxygen' was strong, showing that unrelated photosynthesis products were strongly recognised in 'photosynthesis reactants'.

Low-achievers' learning concept network (Figure 1d) comprised 11 concepts, with the most frequent being 'carbon dioxide' (14 times), 'photosynthesis' (13 times), 'water' (10 times), 'bromothymol blue' (9 times), 'oxygen' (6 times), and 'plant' (6 times). Eigenvector centrality was highest for 'carbon dioxide' (.664), 'water' (.641), 'oxygen' (.264), 'plant' (.189), and 'photosynthesis' (.177). The low-achievers identified the concepts of 'water', 'oxygen', 'photosynthesis', 'plants', and 'carbon dioxide'. Some products, such as 'oxygen', were strongly connected to reactants.

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

In addition, although they were aware of concepts related to inquiry activities, such as 'bromothymol blue', they could not connect them to scientific concepts.

The teaching concept network (Figure 1a) and learning concept networks by high-achievers (Figure 1b) had an identical number of links (54) and the same average degree (4.000), indicating that high-achievers constructed networks highly similar to those of the teachers. The middle-achievers' network (Figure 1c) had 31 links and an average degree of 3.444, while the low-achievers' network (Figure 1d) had 13 links and an average degree of 2.364. Thus, as achievement levels increased, the learning concept networks became more similar in structure to the teaching concept network.

Figure 1
Photosynthesis Reactants' Concept Networks

(a) Teaching concepts

(b) Learning concepts by high-achievers

(c) Learning concepts by middle-achievers

(d) Learning concepts by low-achievers

Photosynthesis Products

The total number of concepts shown in the teaching concepts network (Figure 2a) for 'photosynthesis products' is 35, including 'photosynthesis' (124 times), 'chloroplast' (93 times), 'leaf' (74 times), 'starch' (68 times), and

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

'Hydrilla verticillate' (47 times). The Eigenvector centrality index is in the following order: 'leaf' (.542), 'plant' (.457), 'chloroplast' (.379), 'photosynthesis' (.352), and 'Hydrilla verticillate' (.259). The teaching concepts network is centred around 'photosynthesis', 'leaf', and 'chloroplast', which have high eigenvector centrality indices. Concepts identified in the photosynthesis places and inquiry activities, such as 'chloroplast', 'photosynthesis', 'leaf', and 'Hydrilla verticillate', are presented as the main focus of 'photosynthesis products' rather than 'glucose', 'starch', and 'oxygen'. Through this, it was confirmed that 'photosynthesis products' were explained in relation to the photosynthetic process using inquiry activities.

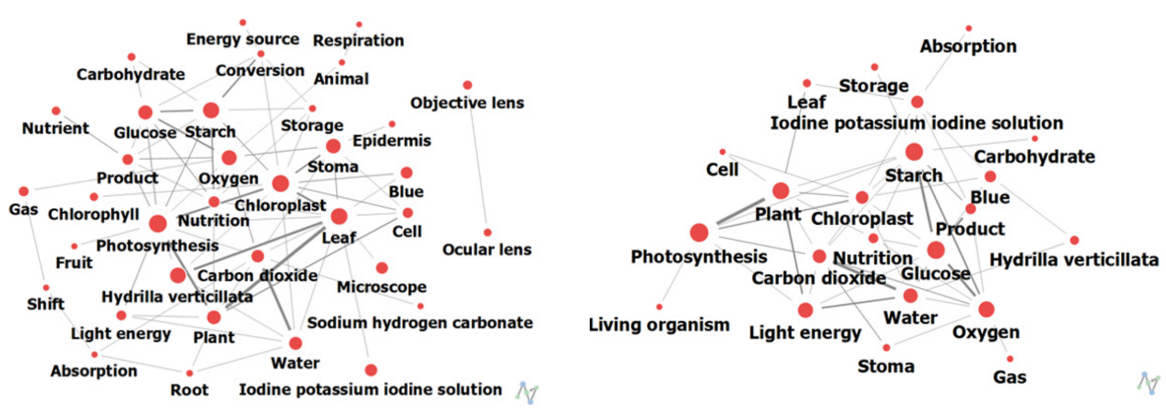
The high-achievers' learning concepts network consists of 22 concepts for 'photosynthesis products' (Figure 2b), including 'photosynthesis' (59 times), 'starch' (35 times), 'glucose' (35 times), 'plant' (34 times), and 'oxygen' (29 times). The eigenvector centrality index is in the following order: 'plant' (.509), 'photosynthesis' (.499), 'glucose' (.288), 'carbon dioxide' (.279), 'water' (.269), and 'starch' (.257). In the high-achievers' learning concepts network, 'starch', 'glucose', and 'oxygen', corresponding to scientific concepts, show high eigenvector centrality and are located at the centre of the network. However, concepts that are somewhat distant from the scientific concept of 'photosynthesis products', such as 'plant', 'chloroplast', 'carbon dioxide', 'light energy', and 'water', are also in the centre.

The total number of concepts shown in the middle-achievers' learning concepts network (Figure 2c) is 20, including 'photosynthesis' (34 times), 'starch' (23 times), 'glucose' (18 times), 'chloroplast' (15 times), and 'water' (15 times). The eigenvector centrality occurs in the following order: 'water' (.569), 'carbon dioxide' (.484), 'light energy' (.371), 'oxygen' (.252), and 'photosynthesis' (.230). The middle-achievers' learning concepts network focused on the concepts of 'starch', 'glucose', and 'chloroplast', corresponding to scientific concepts related to 'photosynthesis products' and are presented with a high frequency. However, the eigenvector centrality is somewhat low, confirming that while students had retained the concept, its connection with other concepts is weak.

The low-achievers' learning concepts network (Figure 2d) comprised 12 concepts, with the most frequent being 'chloroplast' (7 times), 'photosynthesis' (5 times), 'light energy' (5 times), 'oxygen' (5 times), and 'glucose' (4 times). Eigenvector centrality was highest for 'glucose' (.624), 'oxygen' (.558), 'product' (.522), 'starch' (.161), and 'chloroplast' (.001). Scientific concepts such as 'glucose' and 'oxygen' showed high eigenvector centrality, but their connections with other concepts were weak, suggesting that students were recalling them mainly from memory rather than understanding them as part of an integrated conceptual network.

The teaching concept network (Figure 2a) had 72 links and an average degree of 4.114. High-achievers had 50 links and an average degree of 4.545; middle-achievers had 41 links and an average degree of 4.100; low-achievers had 10 links and an average degree of 1.667. Low-achievers' networks were markedly less connected than those of high- and middle-achievers.

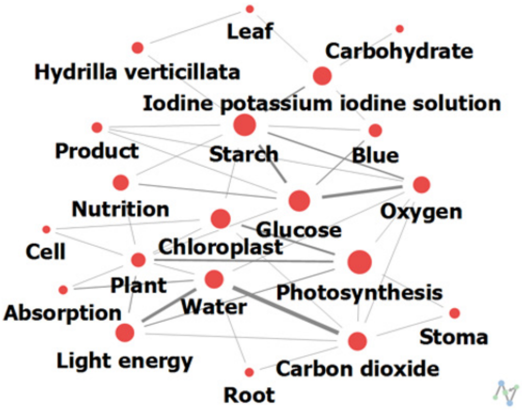
Figure 2
Photosynthesis Products' Concept Networks



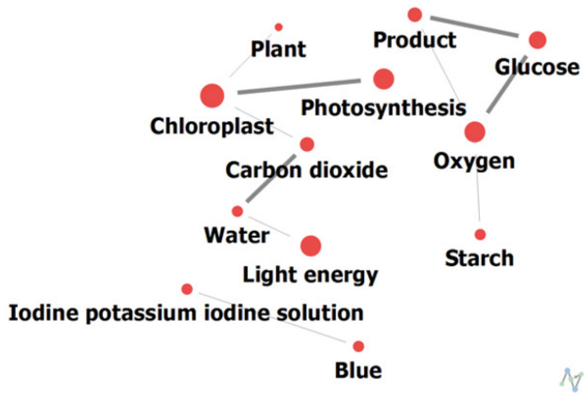
(a) Teaching concepts *(b) Learning concepts by high-achievers*

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/



(c) Learning concepts by middle-achievers



(d) Learning concepts by low-achievers

Environmental Factors

The teaching concepts network for 'environmental factors' (Figure 3a) contained 25 concepts, with the most frequent being 'photosynthesis' (239 times), 'light energy' (166 times), 'light intensity' (120 times), 'carbon dioxide' (95 times), and 'leaf' (95 times). Eigenvector centrality was highest for 'light intensity' (.705), 'light energy' (.703), 'carbon dioxide' (.066), 'temperature' (.043), and 'photosynthesis' (.041). The network is centred on scientific concepts related to 'environmental factors' such as 'light energy', 'light intensity', 'carbon dioxide', and 'photosynthesis'.

The high-achievers' learning concepts network (Figure 3b) contained 16 concepts, with the most frequent being 'photosynthesis' (75 times), 'light energy' (61 times), 'light intensity' (44 times), 'temperature' (34 times), and 'carbon dioxide '(31 times). Eigenvector centrality was highest for 'light intensity' (.688), 'light energy' (.677), 'carbon dioxide' (.157), 'carbon dioxide concentration' (.143), and 'water' (.104). The high-achievers formed a network centred on scientific concepts related to 'environmental factors' such as 'light intensity', 'light energy', 'carbon dioxide', and 'carbon dioxide concentration'. However, 'water', which is not a scientific concept, had a high correlation with 'carbon dioxide'.

The middle-achievers' learning concepts network (Figure 3c) comprises 19 concepts, with the most frequent being 'photosynthesis' (21 times), 'light energy' (19 times), 'light intensity' (11 times), 'oxygen' (11 times), and 'carbon dioxide' (10 times). Eigenvector centrality was highest for 'light energy' (.681), 'light intensity' (.650), 'carbon dioxide' (.228), 'plant' (154), and 'water' (.115). Concepts such as 'light energy', 'light intensity', and 'carbon dioxide' appeared at the centre of the network, but 'temperature' did not. In addition, non-scientific concepts such as 'oxygen' occurred with high frequency, and 'carbon dioxide' was strongly linked to 'water', indicating some conceptual confusion.

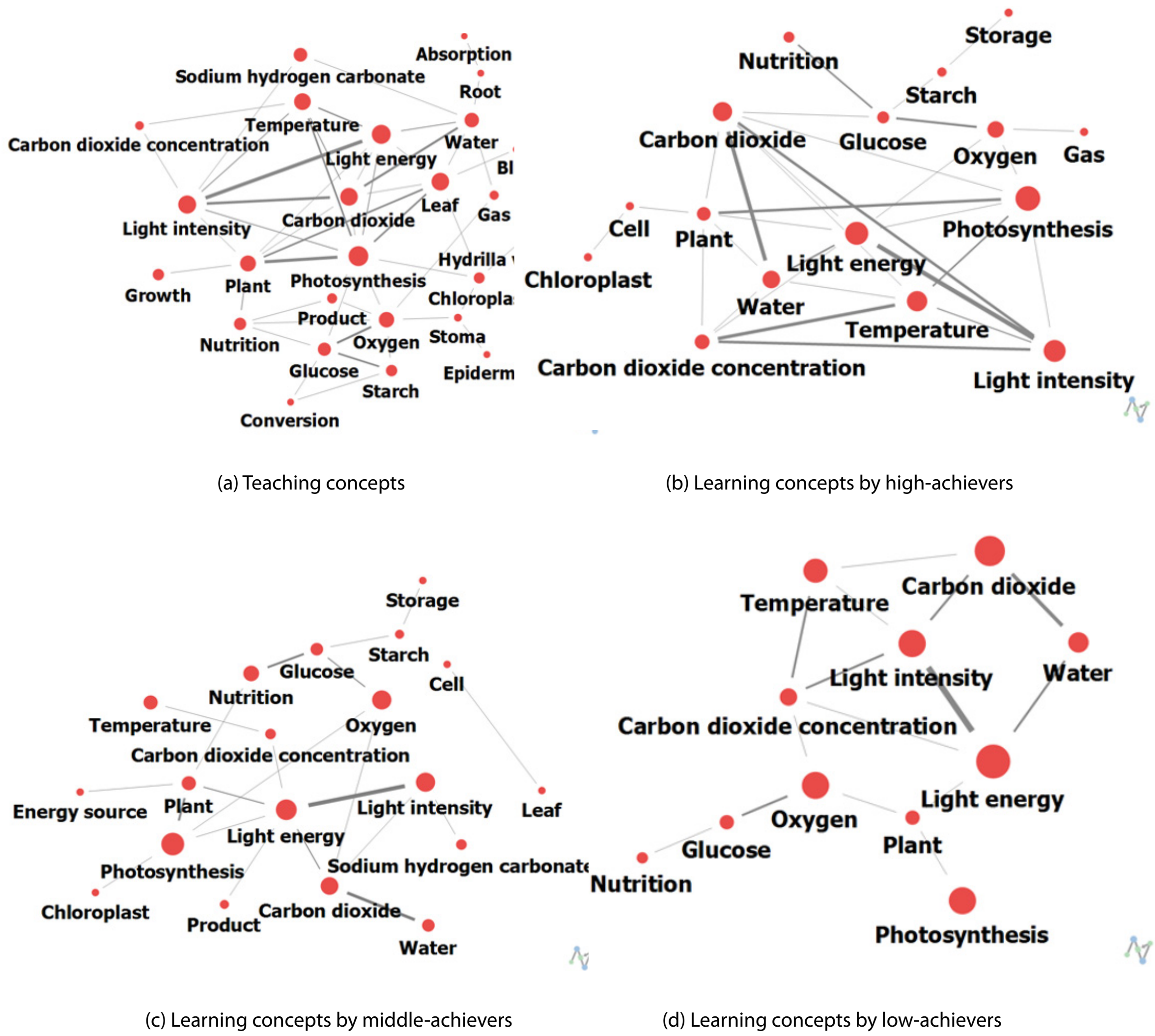
The low-achievers' learning concepts network (Figure 3d) comprised 11 concepts, with the most frequent being 'light energy' (11 times), 'carbon dioxide' (9 times), 'photosynthesis' (7 times), 'light intensity' (7 times), and 'oxygen' (7 times). Eigenvector centrality was highest for 'light intensity' (.637), 'light energy' (.613), 'carbon dioxide concentration' (.263), 'carbon dioxide' (.248), and 'water' (.229). The low-achievers recognised 'light energy', 'light intensity', and 'carbon dioxide' but did not clearly recognise 'temperature'. Additionally, non-scientific concepts related to 'environmental factors', such as 'water' were centred in the network.

The teaching concept network (Figure 3a) had 25 concepts, 50 links, and an average degree of 4.000. The high-achievers' network (Figure 3b) had 16 concepts, 31 links, and an average degree of 3.875, while the middle-achievers' (Figure 3c) had 19 concepts, 21 links, and a lower average degree of 2.211. This indicates that although middle-achievers learned a greater number of concepts (nodes), the connections between concepts (i.e., co-occurrence frequency) were weak, suggesting a fragmented understanding. Additionally, the low-achievers' network (Figure 3d) contained 11 concepts, 15 links, and a lower average degree of 2.727, indicating that as the achievement level decreased, connections between concepts gradually weakened, reflecting a more fragmented understanding.

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

Figure 3
Environmental Factors' Concept Networks



(a) Teaching concepts

(b) Learning concepts by high-achievers

(c) Learning concepts by middle-achievers

(d) Learning concepts by low-achievers

Photosynthesis

The teaching concepts network for the overall topic of photosynthesis (Figure 4a) comprised 44 concepts, with the most frequent being 'photosynthesis' (475 times), 'light energy' (246 times), 'carbon dioxide' (223 times), 'leaf' (177 times), and 'plant' (140 times). The eigenvector centrality was highest for 'light energy' (.693), 'light intensity' (.689), 'carbon dioxide' (.127), 'photosynthesis' (.105), and 'plants' (.089). The network centres around the concepts of 'photosynthesis', 'plant', 'leaf', and 'carbon dioxide'. These results indicate that the teacher explained photosynthesis using light and carbon dioxide, focusing on how it occurs in plants' leaves.

The high-achievers' learning concepts network (Figure 4b) comprised 35 concepts, with the most frequent being 'photosynthesis' (214 times), 'light energy' (148 times), 'carbon dioxide' (119 times), 'water' (89 times), and 'glucose' (81 times). Eigenvector centrality was highest for 'water' (.554), 'carbon dioxide' (.554), 'light energy' (.445), 'light intensity' (.243), and 'photosynthesis' (.232). High-achievers were clearly aware that photosynthesis occurs in plants using water, carbon dioxide, and light. They also comprehended photosynthesis-related content relating to 'glucose', 'plant', 'carbon dioxide', 'oxygen', 'light energy', and 'water'.

The middle-achievers' learning concepts network (Figure 4c) contained 28 concepts, including 'photosynthesis' (101 times), 'carbon dioxide' (71 times), 'light energy' (53 times), 'water' (45 times), and 'glucose' (45 times). Eigenvector centrality was highest for 'carbon dioxide' (.631), 'water' (.630), 'light energy' (.332), 'photosynthesis' (.194), and 'plant'

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

(.166). Across achievement levels, students recognised photosynthesis in relation to the concepts of 'light energy', 'water', 'light intensity', 'carbon dioxide', and 'plant'. In particular, 'carbon dioxide' showed a low correlation with 'photosynthesis', confirming that 'photosynthesis' was comprehended by focusing more on 'light', 'water', and 'plant'.

The low-achievers' learning concepts network (Figure 4d) comprised 19 concepts, including 'carbon dioxide' (26 times), 'photosynthesis' (25 times), 'light energy' (21 times), 'oxygen' (18 times), and 'water' (16 times). The eigenvector centrality index is in the following order: 'water' (.630), 'carbon dioxide' (.625), 'light energy' (.280), 'light intensity' (.210), 'oxygen' (.192), and 'plant' (.156). 'Photosynthesis' was not central, and connections to reactants and products were weak.

Across all achievement levels, higher-achievers learned more concepts and formed more links. The teaching concept network (Figure 4a) had 44 concepts, 113 links, and an average degree of 5.136. High-achievers' networks (Figure 4b) had 35 concepts, 98 links, and an average degree of 5.600, while middle-achievers (Figure 4c) had 28 concepts, 63 links, and an average degree of 4.500. Low-achievers (Figure 4d) had 19 concepts, 29 links, and an average degree of 3.053. These results confirmed that across the topic of photosynthesis, as the achievement level decreases, not only do the number of recognised concepts decrease, but the connections between concepts also gradually diminish, indicating fragmented understanding.

Figure 4
Photosynthesis Concept Networks

(a) Teaching concepts
(b) Learning concepts by high-achievers
(c) Learning concepts by middle-achievers
(d) Learning concepts by low-achievers

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Connection Concept Network

The connection concept network that compares the teaching concepts for each subtopic and the learning concepts based on students' achievement levels is shown in Figure 5. For 'photosynthesis reactants' (Figure 5a), 11 teaching concepts, including 'water', 'glucose', 'Hydrilla verticillata', and 'oxygen', were learned by students at all levels. Among the teaching concepts, high-achievers learned more concepts than low-achievers. High- and middle-achievers learned six common concepts, while low-achievers could not identify any learning concepts. The concepts taught by the teacher but not learned by students were 'animal', 'vessel', and 'sieve tube'. Additionally, high-achievers also learned two concepts not taught by the teacher.

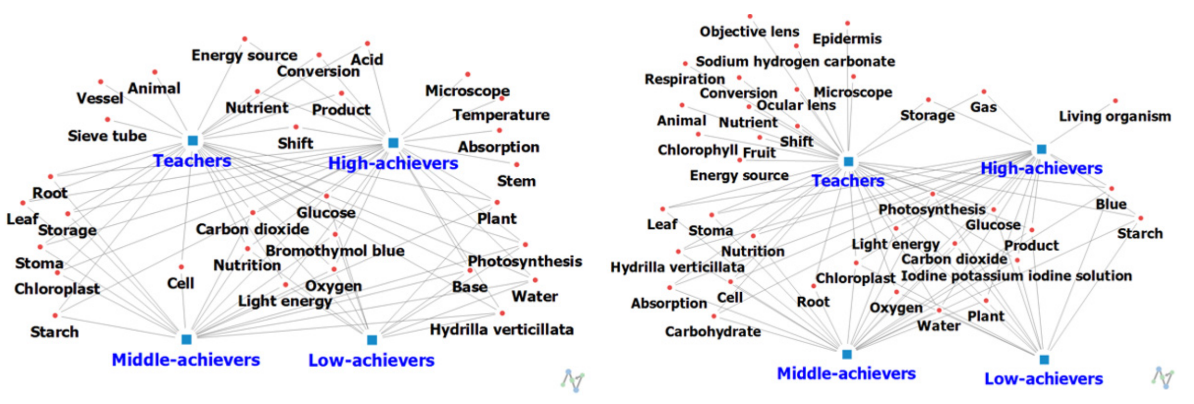
For 'photosynthesis products' (Figure 5b), 12 teaching concepts, including 'glucose', and 'iodine-potassium iodide solution', were learned by students at all levels. The concepts that only high-achievers learned were 'storage' and 'air', and the concept that only middle-achievers learned was 'root'. Thirteen concepts taught by the teacher were not learned by any students, most of which were related to inquiry activities. Furthermore, the high-achievers learned some concepts that the teacher did not teach.

Among the teaching concepts for 'environmental factors' (Figure 5c), 11 concepts, including 'light energy', 'temperature', 'oxygen', and 'water', were learned by students at all levels. Both high- and middle-achievers learned unique concepts, while low-achievers learned none of the additional concepts. Eight concepts taught by the teachers were not learned by the students, including concepts related to inquiry activities. In addition, the high- and middle-achievers demonstrated an understanding of concepts, such as 'gas' and 'energy source', that were not presented in the curriculum and taught by teachers.

Among the teaching concepts for 'photosynthesis' (Figure 5d), 19 concepts, including 'light intensity', 'oxygen', and 'photosynthesis', were learned by students at all achievement levels. Some concepts were learned only by high- and middle-achievers, respectively. Concepts such as 'storage', 'carbohydrate', and 'stoma' were learned by high- and middle-achievers but not low-achievers. Ten concepts taught by teachers were not learned by students at any level, and these were concepts connected to prerequisite learning and subsequent learning.

Overall, students acquired most of the concepts necessary to understand photosynthesis. In other words, students acquired all the necessary concepts for understanding each subtopic. However, students all demonstrated an understanding of concepts not taught by the teacher. (Kim et al., 2023; Lim et al., 2025). Additionally, the number of learning concepts among the teaching concepts tended to increase as the level of academic achievement decreased. Most of the concepts taught by teachers but not learned by students were identified as those presented in the confirmation of prerequisite learning and the introduction to subsequent learning, as well as concepts related to inquiry activities.

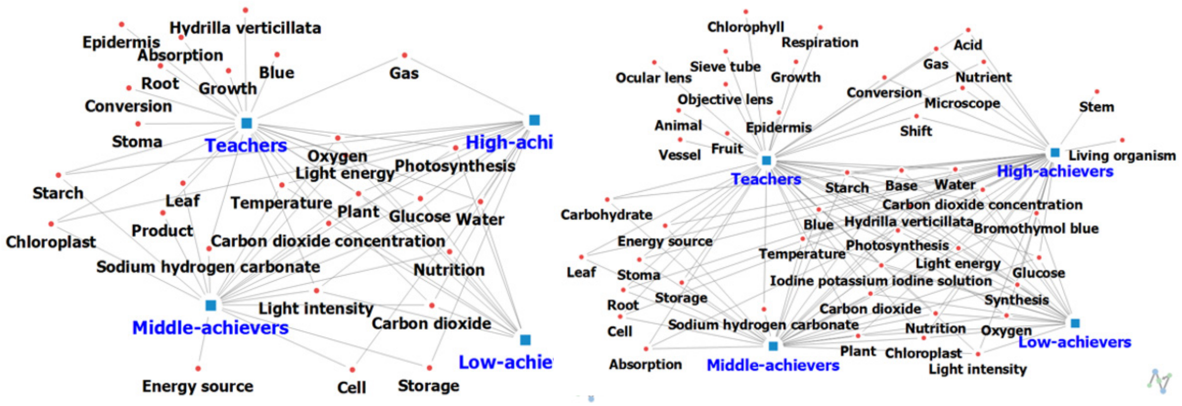
Figure 5
Connection Concept Networks



(a) Photosynthesis reactants (b) Photosynthesis products

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/



(c) Environmental factors

(d) Photosynthesis

Discussion

In this study, the teaching and learning concept networks of photosynthesis in lower-secondary schools in the Republic of Korea were compared through network analysis. The concepts presented in the teaching and learning concept networks were relatively similar (Figure 5), but the degree of connection between concepts differed (Figures 1-4). These results were similar to those of previous research on Mendelian inheritance (Kim et al., 2023; Lim et al., 2025). These results were similar to previous studies on Mendelian heredity, which found that while the concepts presented in the network were relatively similar, the structure of the connections between them differed (Kim et al., 2023; Lim et al., 2025).

The lessons incorporated inquiry activities from the learning of photosynthesis, including experiments presented in the textbooks. Although students learned related concepts through these inquiry activities, they tended to focus on the concepts themselves rather than on the process of the inquiry activities because using concepts to explain scientific phenomena is posy (Cochran-Smith & Lytle, 1999; Duit & Treagust, 2003). Furthermore, considering that novice students tend to apply concepts mechanically (Gentner et al., 2003; Kozma & Russell, 2007), teachers who are experts were required to be more flexible and skilful in teaching by integrating inquiry activities with concepts.

The teacher did not clearly distinguish between subtopics when teaching them. As a result, students could not differentiate subtopics within the concept network (Figure 1-3). Looking at the similar connected concepts between teachers and students (Figure 5), 'photosynthesis', 'water', 'light energy', 'oxygen', 'plants', 'carbon dioxide', and 'glucose' were commonly linked in the subtopics. These results indicate that teachers use common concepts regardless of the subtopic. Because photosynthesis reactants and products are related in terms of processes, the same concepts can be used. However, if the same concepts are presented without considering how to present them when explaining other subtopics, students may become easily confused (Widodo & Duit, 2002; Widodo et al., 2002). This study's results also suggest that students could not distinguish between the concepts related to 'photosynthesis reactants' and 'photosynthesis products' and were confused by the concept network. The use of such confusing concepts can lead to learning deficits by failing to recognise key concepts or even causing errors in connecting concepts (Lim, 2019). Accordingly, concepts should be grouped by subtopic and presented comprehensively. For example, in the case of 'photosynthesis reactants', teachers should present 'carbon dioxide' and 'water' together, and for 'photosynthesis products', 'starch', 'glucose', and 'oxygen' must be presented together.

In the 'environmental factors' class, which is taught according to the sequence of the curriculum in the Republic of Korea, the content learned about 'photosynthesis reactants' and 'photosynthesis products' is repeatedly re-learned (Figure 5c). Such learning likely prevents students from distinguishing between content previously learned and current learning content. In addition, considering that science teachers in the Republic of Korea generally report that more concepts should be taught than what is currently included in the curriculum (Jeong et al., 2010), teachers must boldly exclude concepts unrelated to the learning topic and focus on explaining only those concerning the topic.

Some concepts were present in the teaching concept networks but not in the learning concept networks (Figure 5). The teacher presented these concepts as previously learned to help students understand the topic, but

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

students could not connect them with the new content. In other words, no connection was made between existing and new learning concepts. This pattern is consistent with Lim's (2019) observation that missing concepts or incorrect connections can contribute to learning difficulties. Accordingly, teachers should group and present related concepts that students have already learned as distinct 'chunks' so they can easily recognise them.

Different concepts were acquired depending on the students' academic achievement level. For example, in Figure 5d, only middle-achievers connected nine concepts: 'storage', 'carbohydrate', 'energy source', 'leaf', 'absorption', 'stoma', 'cell', 'root', and 'sodium hydrogen carbonate'. Meanwhile, high-achievers commonly connected six concepts: 'shift', 'nutrients', 'microscope', 'acid', 'gas', and 'conversion'. Furthermore, high-achievers acquired two additional concepts not taught by teachers: 'stem' and 'living organism'. However, middle- and low-achievers learned no concepts other than those taught by teachers.

Students also showed differences in connecting concepts related to photosynthesis depending on their achievement level. High-achievers understood concepts connected to other subtopics and made organic connections between concepts. In addition, the connection to the concepts of high-achievers was relatively similar to that of teachers compared to students at other levels. However, the number of concepts acquired for middle- and low-achievers was relatively low compared to high-achievers, as they appeared to only understand concepts related to that domain. For example, for 'environmental factors', concepts such as 'light energy' or 'carbon dioxide concentration' had more connections with environmental factors (Figure 3). This is consistent with the research results (Lee et al., 2018) showing that high-achievers learned more diverse concepts and have broader concept networks than low-achievers, so high-achievers have more knowledge and make more organic connections among concepts.

Differences also emerged according to achievement level. High-achievers formed more complex networks that were more similar to the teacher's and showed clearer distinctions between subtopics. In contrast, middle- and low-achievers learned fewer concepts and formed weaker connections, often treating concepts in a fragmented manner. These differences may be related to variations in classroom behaviour and engagement (Choi et al., 2022). Teachers should therefore pay particular attention to the participation and attitudes of lower-achieving students.

Conclusions and Implications

This study comparatively analysed the concept networks used by teachers and those constructed by students for the topic of photosynthesis in lower-secondary school. In addition, it analysed the differences in the networks according to students' achievement levels.

The concepts in teaching and learning networks were similar but differed in structure. Most students recognised the teaching concepts for the photosynthesis domain after class. However, although the teacher explained photosynthesis-related concepts through the inquiry activities presented in the textbook, the students remembered and structured them around concepts rather than the inquiry process. These results suggest that teachers must group and present concepts by subtopic. The repeated use of the same concepts across subtopics appeared to hinder students' ability to differentiate content.

High-achievers recognised more concepts, formed stronger connections, and produced networks more similar to the teachers' compared to low-achievers. High-achievers could divide concepts relatively clearly by subtopic, implying a strong understanding of photosynthesis. However, low-achievers' networks had fewer concepts and weaker connections between concepts, showing a lack of connections in many domains. In addition, they were less able to distinguish between concepts by subtopic and connected some concepts incorrectly. Accordingly, teachers need to teach low-achievers to distinguish between concepts by subtopic.

Students failed to learn some of the concepts taught in class, typically those that teachers related to prior learning to facilitate students' comprehension. Therefore, Teachers should explicitly connect prerequisite concepts to the current topic through clear chunking. However, because this study is limited to the concepts learned and retained by students, future research should be conducted on the conceptual structures and perceptions students have in various learning situations, such as problem-solving.

This study has the limitation that it was conducted on only the top 30% of lower-secondary school students in the Republic of Korea, so caution must be exercised when generalizing the results to the entire student population. However, this sampling method was chosen to explore the subtle differences in conceptual connections within the high-achieving student group in order to provide individualized educational support. Future research should expand the sample scope to verify whether the findings of this study can be applied to a more diverse student population.

https://doi.org/10.33225/jbse/26.25.282

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

Declaration of Interest

The authors declare no competing interest.

Ethics statement

According to Article 2 of the Elementary and Secondary Education Act and Article 2 of the Higher Education Act of the Republic of Korea, research related to practical work within the scope of the school curriculum is subject to research ethics exemption. In the course of the research, measures such as obtaining consent were taken after notifying the school, students, and parents that the personal information of students will not be collected or recorded.

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https://doi.org/10.33225/jbse/26.25.282

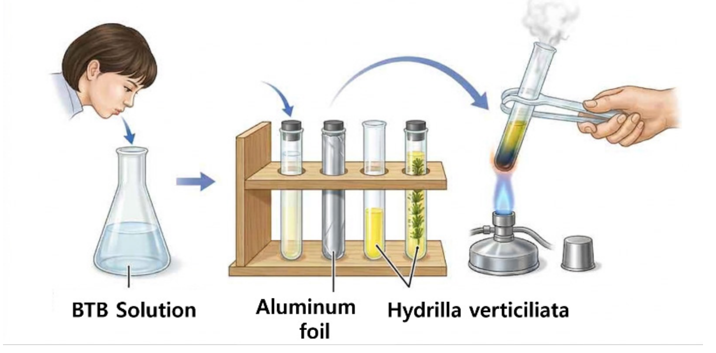
ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Appendix 1. An example of a questionnaire on 'photosynthesis reactants'

[Learning Objectives]

(1) You can explain 'photosynthesis in plants' and 'photosynthesis reactants'.

- This is an experiment to learn about the reactants that plants use for photosynthesis.



[How to Write]

· Refer to the learning objectives and picture and write down what you heard or learned in class in sentence form while studying photosynthesis reactants.

· Please write down as much as possible of everything you remember.

Examples - The degree of diversity of living organisms in a certain area is called biodiversity.

- Humans take in oxygen from the air and expel carbon dioxide from their bodies during respiration, inhaling and exhaling air through the lungs.

Received: *January 13, 2026* Revised: *March 30, 2026* Accepted: *April 09, 2026*

Cite as: Kim, Y., Chun, H., & Lim, S. (2026). Differences in teaching and learning concept networks of photosynthesis according to achievement levels. *Journal of Baltic Science Education*, *25*(2), 282–297. https://doi.org/10.33225/jbse/26.25.282

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